

Standard Model and Graviweak Unification with (Super)Renormalizable Gravity.

Part I: Visible and Invisible Sectors of the Universe

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Abstract

We develop a self-consistent $Spin(4, 4)$ -invariant model of the unification of gravity with weak $SU(2)$ gauge and Higgs fields in the visible and invisible sectors of our Universe. We consider a general case of the graviweak unification, including the higher-derivative super-renormalizable theory of gravity, which is a unitary, asymptotically-free and perturbatively consistent theory of the quantum gravity.

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1 Introduction

In the paper [1], using a general model [2] of the unification of gravity with $SU(N)$ or $SO(N)$ gauge and Higgs fields, we presented a model of unification of gravity with weak $SU(2)$ gauge and Higgs fields, developing the ideas of Ref. [3]. We have considered a $Spin(4, 4)$ -group of the graviweak unification, which is spontaneously broken into the $SL(2, C)^{(grav)} \times SU(2)^{(weak)}$. In contrast to Ref. [1], the main result of this investigation (presented in Part I and Part II) is a case of the graviweak unified model with superrenormalizable gravity. Such a model is constructed in agreement with experimental and astrophysical results. In the present paper we present the embedding of the Standard Model (SM) families into the group of TOE-unification existing at the Planck era. We assume that at the early stage of the evolution of the Universe the TOE-group (for example, E_8 -group) is broken down (say, in $\sim 10^{-43}$ sec after the Big Bang) to the direct product of the gauge groups of internal symmetry and the spacetime Lorentz group:

$$\begin{aligned} G_{TOE} &\rightarrow G_{(Graviweak)} \times U(4) \rightarrow SL(2, C)^{(grav)} \times SU(2)^{(weak)} \times U(4) \\ &\rightarrow SL(2, C)^{(grav)} \times SU(3)_{(color)} \times SU(2)^{(weak)} \times U(1)_Y \times U(1)_{(B-L)} \\ &\rightarrow SL(2, C)^{(grav)} \times SU(3)_{(color)} \times SU(2)^{(weak)} \times U(1)_Y. \end{aligned}$$

Thus, below the sea-saw scale ($M_R \sim 10^9 - 10^{14}$ GeV) we have the SM-group of symmetry:

$$G_{SM} = SL(2, C)^{(grav)} \times SU(3)_{(color)} \times SU(2)^{(weak)} \times U(1)_Y.$$

Spinors appear in multiplets of the gauge groups. Here it is necessary to emphasize that in our graviweak unified model there exists a large breaking scale for supersymmetry (more than 10^{18} GeV). Also we assume the existence in Nature of the invisible (mirror, or hidden) world parallel to the visible Ordinary World (OW) [4–7]. In our present paper this hidden sector of the Universe is a Mirror World (MW) with broken Mirror Parity (MP) (see Refs. [8–12] and reviews [13–15]). The first part (Part I) of our investigation ”Standard Model and Graviweak Unification” is devoted to the main idea of Plebanski to describe gravity by connections and tetrads as independent variables, to the problem of the hidden sector of our Universe and to the calculation of the action of the graviweak unification with (super)renormalizable gravity. The second part - Part II - is devoted to the main properties of the graviweak unified model with (super)renormalizable gravity – asymptotic freedom and the problem of unitarity, calculation of all coupling constants of theory and consideration of their flow equations. Also the difference of coupling constants in the ordinary and hidden sectors is discussed. The paper is organized as follows. Section 2 is devoted to the visible and invisible sectors of our Universe. In Subsection 2.1 we consider the existence of the Mirror World (MW), which is a mirror copy of the Ordinary World (OW) and contains the same particles and types of interactions as our visible world. In Subsection 2.2 we assume that our Universe has a mirror (hidden) world

with a broken Mirror Parity (MP): the Higgs VEVs of the visible and invisible worlds are not equal ¹, $\langle\phi\rangle = v$, $\langle\phi'\rangle = v'$ and $v \neq v'$. The parameter characterizing the violation of the MP is $\zeta = v'/v \gg 1$. We are using the estimate $\zeta \simeq 100$. In Section 3 we introduce the main ideas of the Plebanski's theory of gravity. Section 4 is devoted to the problem of the existence of the mirror (hidden) world in Nature. In Sections 5 and 6 we constructed a model of the unification of super-renormalizable gravity with weak $SU(2)$ gauge and Higgs fields. This GWU model, including the higher-derivative super-renormalizable theory of gravity is unitary, asymptotically-free and perturbatively consistent theory of the quantum gravity. We considered the renormalization group flow of the higher derivative gravity in the 1-loop approximation, i.e. the RGE for the running of the super-renormalizable gravitational coupling constants, predicted by our graviweak unification model. The theory is described by the overall unification parameter g_{uni} . It was shown that this self-consistent GWU exists only at the high (Planck) scale. The graviweak unification model in both, left-handed and right-handed (visible and invisible) sectors of the Universe, was considered in Subsection 5.4, where we presented the actions for both sectors of the Universe, visible and mirror. Section 7 contains a summary and conclusions.

2 Visible and invisible sectors of our Universe

2.1 Mirror World

Refs. [4–15] suggest the hypothesis of the existence in Nature of the invisible mirror (or hidden) world – parallel to the visible (ordinary) one. The Mirror World (MW) is a mirror copy of the Ordinary World (OW) and contains the same particles and types of interactions as our visible world. The observable elementary particles have left-handed (V-A) weak interactions, which violate P-parity. If a hidden MW exists, then mirror particles participate in the right-handed (V+A) weak interactions and have the opposite chirality. Lee and Yang were the first [4] to suggest such a duplication of the worlds, which restores the left-right symmetry of the Nature. The term "Mirror Matter" was introduced by Kobzarev, Okun and Pomeranchuk [5]. They first suggested the MW as the hidden (invisible) sector of the Universe, which interacts with the ordinary (visible) world only via gravity, or another very weak interaction. They have investigated a variety of phenomenological implications of such parallel worlds (see reviews [13,14]). The SM group of symmetry G_{SM} was enlarged to $G_{SM} \times G'_{SM'}$, where G_{SM} stands for the observable SM, while $G'_{SM'}$ is its mirror gauge counterpart. These different worlds are coupled only by gravity, or another very weak interaction [4–7]. Superstring theory also predicts that there may exist in the Universe another form of matter – hidden (or 'shadow') matter, which only interacts with ordinary matter via gravity or another gravitational-strength

¹In this paper the superscript 'prime' denotes the M- (or hidden H-) world.

interactions [6, 7]. According to the superstring theory, these two worlds, ordinary and hidden, can be sometimes (not always) very different – at least unless we start the two worlds up with the same quantum numbers. In general case, we must distinguish initial conditions and the equations of motion. These two worlds can be viewed as parallel branes in a higher dimensional space, where visible particles are localized on the one brane and hidden particles – on the another brane, and gravity propagates in the bulk. In Refs. [16–18] we considered the theory of the superstring-inspired E_6 unification with different types of the breaking of the E_6 symmetry in the visible and hidden worlds.

2.2 Mirror world with broken mirror parity

If the ordinary and mirror worlds are identical, then O- and M-particles should have the same cosmological densities. But this is immediately in conflict with recent astrophysical measurements if the MW-density should be identified with Dark Matter. Astrophysical and cosmological observations (see for example [19, 20]) have revealed the existence of the Dark Matter (DM) which constitutes about 25% of the total energy density of the Universe. This is five times larger than all the visible matter, $\Omega_{DM} : \Omega_M \simeq 5 : 1$. Mirror particles have been suggested as candidates for the inferred dark matter in the Universe (see Refs. [8–15]). Therefore, the mirror parity (MP) is not conserved, and the OW and MW are not identical. In Refs. [8–11] it was suggested that the VEVs of the Higgs doublets $\phi(= H)$ and $\phi'(= H')$ are not equal:

$$\langle \phi \rangle = v, \quad \langle \phi' \rangle = v' \quad \text{and} \quad v \neq v'. \quad (1)$$

The parameter characterizing the violation of MP:

$$\zeta = \frac{v'}{v} \gg 1 \quad (2)$$

was introduced and estimated in Refs. [8–11] and [21–24]:

$$\zeta > 30, \quad \zeta \sim 100. \quad (3)$$

Then the masses of mirror fermions and massive bosons are scaled up by the factor ζ with respect to the masses of their OW-counterparts:

$$m'_{q',l'} = \zeta m_{q,l}, \quad (4)$$

and

$$M'_{W',Z',\phi'} = \zeta M_{W,Z,\phi}, \quad (5)$$

while photons and gluons remain massless in both worlds. In the language of neutrino physics, the O-neutrinos ν_e, ν_μ, ν_τ are active neutrinos, and the M-neutrinos $\nu'_e, \nu'_\mu, \nu'_\tau$ are sterile neutrinos [21]. If MP is conserved ($\zeta = 1$), then the neutrinos of the two

sectors are strongly mixed (see Refs. [8–11]). However, the present experimental and cosmological limits on the active-sterile neutrino mixing do not confirm this result. The ‘neutrino-mirror neutrino’ oscillations were investigated in Refs. [21, 25–27]. In Refs. [28, 29] the exact parity symmetry explains the solar neutrino deficit, the atmospheric neutrino anomaly and the LSND experiment. In the context of the SM, in addition to the fermions with non-zero gauge charges, one introduces also the gauge singlets, the so-called right-handed neutrinos N_a with large Majorana mass terms. They have equal masses in the OW and MW [8, 9]:

$$M'_{\nu,a} = M_{\nu,a}. \quad (6)$$

According to the usual seesaw mechanism [30], heavy right-handed neutrinos are created in the OW at the seesaw scale $M_R \sim 10^9 - 10^{14}$ GeV.

3 Gravity in the Plebanski’s formulation of General Relativity

Originally General Relativity (GR) was formulated by Einstein as the dynamics of a metric, $g_{\mu\nu}$. Later Plebanski [31], Ashtekar [32, 33] and other authors [34, 35] presented GR in a self-dual approach, in which the true configuration variable is a self-dual connection corresponding to the gauging of the local Lorentz group, $SO(1, 3)$, or the spin group, $Spin(1, 3)$. In the unification models [1, 2], the fundamental variable is a connection, A , valued in a Lie algebra, \mathfrak{g} , that includes a subalgebra $\tilde{\mathfrak{g}}$:

$$\tilde{\mathfrak{g}} = \mathfrak{g}^{(spacetime)} \oplus \mathfrak{g}_{YM}, \quad (7)$$

which is the direct sum of the Lorentz algebra and a Yang–Mills gauge algebra. Previously graviweak and gravi-electro-weak unified models were suggested in Ref. [37–39]. The gravi-GUT unification was developed in [40–43]. In the Plebanski’s formulation of the 4-dimensional theory of gravity [31], the gravitational action is the product of two 2-forms (see [31–35] and [44–48]), which are constructed from the connections A^{IJ} and tetrads (or frames) e^I considered as independent dynamical variables. Both A^{IJ} and e^I are 1-forms:

$$A^{IJ} = A^{IJ}_\mu dx^\mu \quad \text{and} \quad e^I = e^I_\mu dx^\mu. \quad (8)$$

The indices $I, J = 0, 1, 2, 3$ refer to the spacetime with Minkowski metric η_{IJ} : $\eta^{IJ} = \text{diag}(1, -1, -1, -1)$. This is a flat space which is tangential to the curved space with the metric $g_{\mu\nu}$. The world interval is represented as $ds^2 = \eta_{IJ} e^I \otimes e^J$, i.e.

$$g_{\mu\nu} = \eta_{IJ} e^I_\mu \otimes e^J_\nu. \quad (9)$$

Considering the case of the Minkowski flat spacetime with the group of symmetry $SO(1, 3)$, we have the capital latin indices $I, J, \dots = 0, 1, 2, 3$, which are vector indices under the

rotation group $SO(1, 3)$. The 2-forms B^{IJ} and F^{IJ} are defined as:

$$B^{IJ} = e^I \wedge e^J = \frac{1}{2} e_\mu^I e_\nu^J dx^\mu \wedge dx^\nu, \quad F^{IJ} = \frac{1}{2} F_{\mu\nu}^{IJ} dx^\mu \wedge dx^\nu. \quad (10)$$

Here the tensor $F_{\mu\nu}^{IJ}$ is the field strength of the spin connection A_μ^{IJ} :

$$F_{\mu\nu}^{IJ} = \partial_\mu A_\nu^{IJ} - \partial_\nu A_\mu^{IJ} + [A_\mu, A_\nu]^{IJ}, \quad (11)$$

which determines the Riemann–Cartan curvature:

$$R_{\kappa\lambda\mu\nu} = e_\kappa^I e_\lambda^J F_{\mu\nu}^{IJ}. \quad (12)$$

In the Plebanski BF-theory, the gravitational action with nonzero cosmological constant Λ is given by the integral:

$$I_{GR} = \frac{1}{\kappa^2} \int \epsilon^{IJKL} \left(B^{IJ} \wedge F^{KL} + \frac{\Lambda}{4} B^{IJ} \wedge B^{KL} \right), \quad (13)$$

where $\kappa^2 = 8\pi G_N$, G_N is the gravitational constant, $M_{Pl}^{red.} = 1/\sqrt{8\pi G_N}$. For any antisymmetric tensors $F_{\mu\nu}$ and A^{IJ} there exist dual tensors given by the Hodge star dual operation:

$$F_{\mu\nu}^* \equiv \frac{1}{2\sqrt{-g}} \epsilon_{\mu\nu}{}^{\rho\sigma} F_{\rho\sigma}, \quad A^{*IJ} = \frac{1}{2} \epsilon^{IJ}{}_{KL} A^{KL}. \quad (14)$$

Here ϵ is the completely antisymmetric tensor with $\epsilon^{0123} = 1$. We can define the algebraic self-dual (+) and anti-self-dual (-) components of A^{IJ} :

$$A^{(\pm)IJ} = (\mathcal{P}^\pm A)^{IJ} = \frac{1}{2} (A^{IJ} \pm i A^{*IJ}), \quad (15)$$

and as a result we have:

$$A^{(+)} = -i A^{*(-)}, \quad A^{(-)} = i A^{*(+)}, \quad (16)$$

or

$$A^{*(+)} = -i A^{(-)}, \quad A^{*(-)} = i A^{(+)}. \quad (17)$$

The two projectors $\mathcal{P}^\pm = \frac{1}{2}(\delta_{KL}^{IJ} \pm \frac{i}{2}\epsilon_{KL}^{IJ})$ realize explicitly the familiar homomorphism:

$$SO(1, 3)_C = SL(2, C)_L \otimes SL(2, C)_R, \quad (18)$$

or

$$\mathfrak{so}(1, 3)_C = \mathfrak{sl}(2, C)_L \oplus \mathfrak{sl}(2, C)_R, \quad (19)$$

which rather than self-dual (+) and anti-self-dual (-) are more commonly dubbed right-handed (R) and left-handed (L). If we consider a Wick rotation in the gravitational theory,

replacing the time t by imaginary time $t' = it$, then we obtain the gravity in the Euclidean spacetime with $SO(4)$ -group of symmetry (see for example [46]), and instead of Eqs. (18) and (19), we have:

$$SO(4) = SU(2)_L \otimes SU(2)_R, \quad (20)$$

or

$$\mathfrak{so}(4) = \mathfrak{su}(2)_L \oplus \mathfrak{su}(2)_R. \quad (21)$$

The self-dual and anti-self-dual tensors $A^{(\pm)IJ}$ have only three independent components given by $IJ = 0i$, where $i = 1, 2, 3$. To make the mapping more explicit, it is convenient to pick out the time direction equal to zero, and define:

$$A^{(\pm)i} = \pm 2A^{(\pm)0i} \quad (22)$$

with $i = 1, 2, 3$. The correct gauge was provided by Plebanski, when he introduced in the gravitational action the Lagrange multipliers ψ_{ij} – an auxiliary fields, symmetric and traceless. These auxiliary fields provide a correct number of constraints, and we obtain the following gravitational action:

$$I_{gravity}(\Sigma, A, \psi) = \frac{1}{\kappa^2} \int [\Sigma^i \wedge F^i + (\Psi^{-1})_{ij} \Sigma^i \wedge \Sigma^j]. \quad (23)$$

The usual notations:

$$\Sigma^i = 2B^{0i}, \quad (24)$$

and

$$(\Psi^{-1})_{ij} = \psi_{ij} - \frac{\Lambda}{6} \delta_{ij} \quad (25)$$

are presented in action given by Eq. (23). Following the ideas of Ref. [3], we distinguish the two worlds of the Universe, visible and invisible, and consider the two sectors of gravity: left-handed gravity and right-handed gravity. The self-dual left-handed gravity is described by the following action:

$$I_{(OW)}^{(grav)}(\Sigma^{(+)}, A^{(+)}, \psi) = \frac{1}{\kappa^2} \int [\Sigma^{(+i)} \wedge F^{(+i)} + (\Psi^{-1})_{ij} \Sigma^{(+i)} \wedge \Sigma^{(+j)}]. \quad (26)$$

Using the simpler self-dual variables instead of the full Lorentz group, Plebanski [31] and the authors of Refs. [32–35] suggested to consider in the visible sector of our Universe the left-handed $\mathfrak{sl}(2, C)_L^{(grav)}$ -invariant gravitational action (26) with self-dual fields $F^{(+i)}$ and $\Sigma^{(+i)}$. If there exists in Nature a duplication of worlds with opposite chiralities - Ordinary and Mirror – we can consider the left-handed gravity in the Ordinary world and the right-handed gravity in the Mirror world. The anti-self-dual right-handed gravitational action of the mirror world MW is given by the following integral:

$$I_{(MW)}^{(grav)}(\Sigma^{(-)}, A^{(-)}, \psi') = \frac{1}{\kappa'^2} \int [\Sigma^{(-i)} \wedge F^{(-i)} + (\Psi'^{-1})_{ij} \Sigma^{(-i)} \wedge \Sigma^{(-j)}]. \quad (27)$$

In Eqs. (26) and (27) we have:

$$\Sigma^{(\pm)i} = e^0 \wedge e^i \pm i \frac{1}{2} \epsilon_{jk}^i e^j \wedge e^k. \quad (28)$$

The self-dual action (26) is equivalent to the Einstein-Hilbert action for general relativity with the Einstein's cosmological constant Λ [31]:

$$I_{EH} = -\frac{1}{\kappa^2} \int d^4x \sqrt{-g} \left(\frac{1}{2} R - \Lambda \right), \quad (29)$$

where R is a scalar curvature. A problem of constraints in the Plebanski's theory of GR was in detail studied in Refs. [35, 36] (see also [44–46]). Plebanski considered the action (26) with the following constraints:

$$\Sigma^{(+i} \wedge \Sigma^{+j)} - \frac{1}{3} \delta^{ij} \Sigma^{(+k} \wedge \Sigma_k^{+)} = 0, \quad (30)$$

and

$$\Sigma^{(+i} \wedge \Sigma^{(-j)} = 0. \quad (31)$$

The variables $\Sigma_{\mu\nu}^i$ have 18 degrees of freedom. The five conditions (30) leave 13 degrees of freedom, and the condition (31) leaves 10 degrees of freedom, which coincides with a number of degrees of freedom given by the metric tensor $g_{\mu\nu}$. This circumstance confirms the equivalence of the actions (26) and (29). And now we have the following groups describing GR:

$$\mathfrak{so}(1, 3)_C = \mathfrak{sl}(2, C)_L \oplus \mathfrak{sl}(2, C)_R. \quad (32)$$

If the anti-self-dual right-handed gravitational world is absent in Nature ($\Sigma^{(-)} = 0$ and $F^{(-)} = 0$), then the gravity of our world, in which we live, is presented only by the self-dual left-handed Plebanski action (26) equivalent to the Einstein-Hilbert's gravity (29). This is a main assumption of Plebanski. The same self-dual formulation of General Relativity was developed later by Ashtekar [32, 33]. In Section 4 and below we wish to use the following notations for $X = A, B, F, \Sigma$:

$$X = X^{(+)}, \quad X' = X^{(-)}.$$

4 Does the Mirror or Hidden world of the Universe really exist?

Here we can consider four possibilities.

I) The mirror right-handed world is absent in the Universe: the mirror particles and the mirror gravity do not exist in Nature, what means that $\Sigma' = \Sigma^{(-)} = 0$ and the right-handed connection $A' = A_R = A^{(-)} = 0$.

II) The mirror (or hidden) right-handed world is separated from the visible (ordinary) left-handed one, $\Sigma = \Sigma^{(+)} \neq 0$, $\Sigma' = \Sigma^{(-)} \neq 0$, and the connections $A = A_L = A^{(+)}$, $A' = A_R = A^{(-)}$ are not zero, but the ordinary and mirror gravitational fields do not interact directly. There are several fundamental ways by which the mirror (hidden) world can communicate with our visible world. Two worlds can interact via a very weak interaction of the singlet scalar fields. It was shown in Ref. [49] that an ultralight scalar field with mass around $10^{-22} - 10^{-23}$ eV is a viable dark matter candidate, and this field can be detected by the planned SKA pulsar timing array experiments (see [50]), which considered the gravitational field of the galactic halo composed of such dark matter. The authors of Ref. [51] suggested that there exists an interaction between the ordinary and mirror Higgs doublets, ϕ and ϕ' , respectively:

$$L_H = \lambda_1 (\phi^\dagger \phi) (\phi'^\dagger \phi'). \quad (33)$$

In Ref. [52] the existence of the additional interaction:

$$L_Y = \epsilon_Y F_{Y,\mu\nu} F_Y'^{\mu\nu} \quad (34)$$

was assumed, where $F_{Y,\mu\nu}$ and $F_Y'^{\mu\nu}$ are the $U(1)_Y$ and $U(1)'_Y$ field strength tensors, respectively.

Also the right-handed Majorana neutrinos N_a can communicate between visible and hidden worlds (see for example [53, 54]).

III) (a) The third possibility concerns the theory of the strong mixing of $g_{\mu\nu}^{L,R}$ – the so called "bigravity theory" (see for example [55]). It was assumed in [55] that ordinary matter and mirror matter interact with two separate metric tensors $g_{\mu\nu}^L$ and $g_{\mu\nu}^R$, i.e. each sector has its own GR-like gravity. The effective action of this model contains Einstein-Hilbert terms in each sector and a mixing term between the two sectors:

$$I = \int d^4x [\sqrt{g^L} (\frac{M_{Pl}}{2} R^{(L)} + L_1) + \sqrt{g^R} (\frac{M_{Pl}}{2} R^{(R)} + L_2) + (g_L g_R)^{1/4} L_{mix}], \quad (35)$$

where L_1 and L_2 are the Lagrangians respectively for the ordinary and mirror particles/fields, and L_{mix} again describes possible interaction terms between the ordinary and mirror worlds.

(b) The mixing of $g_{\mu\nu}^{L,R}$ can be so strong that the left-handed gravity coincides with the right-handed gravity: the left-handed and right-handed connections are equal, $A = A'$, i.e. $A_L = A_R$, what means that a dual part A^* of the connection is zero. In this case $g_{\mu\nu}^L = g_{\mu\nu}^R$, and the left-handed and right-handed gravity equally interact with visible and mirror matters. To describe the real world we have to restrict the solutions of theory to those in which the metric is real. In spite of the fact that the metric is not a fundamental field in the Plebanski action, we can specify the modified reality conditions. For this purpose, it is convenient to consider the two component spinor indices (see for example [47]): $a, b = 0, 1$ are left handed spinor indices, while $a', b' = 0', 1'$ are right

handed spinor indices. This allows us to easily distinguish the left and right handed fields. The connection decomposes into:

$$A^{IJ} = A^{aa'bb'} = \epsilon^{ab} A^{a'b'} + A^{ab} \epsilon^{a'b'}, \quad (36)$$

and the two forms B^{IJ} similarly decompose. The remarkable fact is that the constructed metric is cubic in B -fields [35, 39]. In fact, two metrics can be built, out of the left and right parts of B (or Σ), which are called the left and right Urbantke metrics [35, 39]:

$$g_{\mu\nu}^L = \epsilon^{\alpha\beta\gamma\delta} B_{\mu\alpha}^a B_{\nu\beta}^b B_{\gamma\delta}^c, \quad (37)$$

$$g_{\mu\nu}^R = \epsilon^{\alpha\beta\gamma\delta} B_{\mu\alpha}^{a'} B_{\nu\beta}^{b'} B_{\gamma\delta}^{c'}, \quad (38)$$

in which $\epsilon^{\alpha\beta\gamma\delta}$ is the Levi-Civita symbol. In the Minkowski spacetime background, in low energy limit, the metric can be expanded by the Feynman expansion:

$$g_{\mu\nu}^{L,R} = \eta_{\mu\nu} + \kappa_{L,R} h_{\mu\nu}^{L,R}, \quad (39)$$

where $h_{\mu\nu}^{L,R}$ are left- and right-handed gravitons, respectively. Considering the interaction between ordinary and mirror worlds, we can discuss a phenomenology of the two gravitons $h_{\mu\nu}^{L,R}$. Then a parity even combination:

$$h_{\mu\nu} = h_{\mu\nu}^L + h_{\mu\nu}^R \quad (40)$$

will be massless due to the diffeomorphism invariance, and will correspond to the standard graviton. This graviton couples universally to L- and R- matters. On the other hand, the parity odd combination:

$$\tilde{h}_{\mu\nu} = h_{\mu\nu}^L - h_{\mu\nu}^R \quad (41)$$

is not protected by diffeomorphisms and may be massive. If the parity odd graviton \tilde{h} has the Planck-scale mass, then it would be unobservable at low energy. In this case, there exists the overall gravity in the Universe, and the ordinary (visible) world interacts with the mirror (hidden) world via this gravity. Theory III) depends on details of the full theory at energy beyond the Planck scale. If the parity odd graviton $\tilde{h}_{\mu\nu}$ is sufficiently light, then it would give rise to the polarization-dependent gravitational effects during the detection of the gravitational waves in the CMB or pulsar timing programs. Then the parity violation is applied not only to the weak interaction, but also to the gravitational sector. The parity violation of gravity was considered in Ref. [56], which proposed a test of this effect through coincident observations of gravitational waves and short gamma-ray bursts from binary mergers involving neutron stars. Such gravitational waves are highly left or right circularly-polarized due to the geometry of the merger. Using localization information from the gamma-ray burst, ground-based gravitational wave detectors can measure the distance to the source with reasonable accuracy. Gravitational parity violation would manifest itself as a discrepancy between the distance measurements. The effective theory,

leading to such gravitational parity-violation, is the Chern-Simons theory of gravity [57]. The future experiments detecting the parity non-conservation in gravity are planning in the framework of the development of the future investigations of CMB [58–61]. If our Universe has chosen the picture III, then the dynamics of the total Universe, visible and invisible, is governed by the following action:

$$I = \int d^4x (L_{(grav)} + L_{SM} + L'_{SM'} + L_{(mix)}), \quad (42)$$

where $L_{(grav)}$ is the gravitational (Einstein-Hilbert) low-energy Lagrangian, describing gravity in both (O- and M-) worlds, L_{SM} and $L'_{SM'}$ are the Standard Model Lagrangians in the O- and M-worlds, respectively, $L_{(mix)}$ is the Lagrangian describing all mixing terms, which give very small contributions to physical processes: mirror particles have not been seen so far, and the communication between visible and hidden worlds is hard. Searching for mirror particles at the LHC was discussed in Ref. [62]. We can imagine that a fraction of the mirror matter exists in the form of mirror galaxies, mirror stars, mirror planets, etc. (see for example Refs. [63–65]). These objects can be detected by the gravitational microlensing methods [64]. Such researches show fascinating results (see for example [14] and [15]). A Nature of our Universe can be understood by future experiments with CMB, similar to WMAP, "Hubble", "Planck", "BICEP2" [58–61], and also depends on the future LHC results.

5 Graviweak unified model with renormalizable gravity

Developing the graviweak unification model in the visible sector of the Universe, we started in Ref. [1] with a $\mathfrak{g} = \mathfrak{spin}(4, 4)$ -invariant extended Plebanski's action:

$$I(A, B, \Phi) = \frac{1}{g_{uni}} \int_{\mathfrak{M}} \langle BF + B\Phi B + \frac{1}{3}B\Phi\Phi B \rangle. \quad (43)$$

The wedge product $\langle \dots \rangle$ is assumed between the forms. The action (43) contains a parameter of the unification g_{uni} . The connection, $A = \frac{1}{2}A^{IJ}\gamma_{IJ}$, is an independent physical variable describing the geometry of the spacetime, while B and Φ are considered as auxiliary fields [2]. All 2-forms, $F = \frac{1}{2}F^{IJ}\gamma_{IJ}$ and $B = \frac{1}{2}B^{IJ}\gamma_{IJ}$, are $\mathfrak{spin}(4, 4)$ -valued fields. Here $F = dA + \frac{1}{2}[A, A]$. The fields F^{IJ} and B^{IJ} again are given by Eqs. (10) and (11), but now the indices I, J run over all 8×8 values: $I, J = 1, 2, \dots, 7, 8$ ($I, J = 1, 5, 6, 7$ - timelike components, and $I, J = 2, 3, 4, 8$ - spatial ones). The auxiliary field Φ is a symmetric linear operator, which transforms bivectors to bivectors and 2-forms to 2-forms, it has the indices $\Phi_{\mu\nu}{}^{\rho\sigma IJ}{}_{KL}$. As an example, the second term of the action (43) is

$$\langle B\Phi B \rangle = \frac{1}{32} \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu IJ} \Phi_{\rho\sigma}{}^{\varphi\chi IJ}{}_{KL} B_{\varphi\chi}{}^{KL} d^4x. \quad (44)$$

The field equations obtained by varying the fields A, B and Φ are:

$$\mathcal{D}B = dB + [A, B] = 0, \quad (45)$$

where \mathcal{D} is the covariant derivative, $\mathcal{D}_\mu^{IJ} = \delta^{IJ}\partial_\mu - A_\mu^{IJ}$,

$$F = -2 \left(\Phi + \frac{1}{3} \Phi \Phi \Phi \right) B, \quad (46)$$

and

$$\frac{1}{32} \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu IJ} B_{\varphi\chi}{}^{KL} = -\frac{1}{512} \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu IJ} \Phi_{\varphi\chi}{}^{\psi\omega KL}{}_{MN} \Phi_{\psi\omega}{}^{\xi\zeta MN}{}_{PQ} B_{\xi\zeta}{}^{PQ}. \quad (47)$$

The first equation (45) describes the dynamics, while Eqs. (46) and (47) determine the auxiliary fields B and Φ . The specific action (43) with the "Mexican hat" potential for Φ has been chosen here in accordance with Ref. [2], because such a choice allows symmetry breaking to a non-trivial vacuum expectation value (VEV). Of course, more general actions with arbitrary potential, $U(\Phi)$, can also be chosen for another type of unification. But here we consider the action (43), which leads to a simple analysis.

5.1 Symmetry breaking

According to Refs. [1] and [2], we can present the following spontaneous symmetry breaking of the \mathfrak{g} -invariant action (43):

$$\tilde{\mathfrak{g}} = \mathfrak{sl}(2, C)_L^{(grav)} \oplus \mathfrak{su}(2)_L. \quad (48)$$

Below the indices $a, b \in \{0, 1, 2, 3\}$ are used to sum over a subset of $I, J \in 1, 2, \dots, 7, 8$ for $I, J = 1, 2, 3, 4$, and thereby select a $\mathfrak{spin}(1, 3)$ subalgebra of $\mathfrak{spin}(4, 4)$. The indices $m, n \in \{5, 6, 7, 8\}$ sum over the rest. We also consider $i, j \in \{1, 2, 3\}$, thus selecting $\mathfrak{sl}(2, C)_{L,R}^{grav}$ subalgebras of $\mathfrak{spin}(4, 4)$. The equations of motion (45)-(47) help us to obtain a symmetry breaking ansatz for Φ (of course, phenomenologically assuming no breaking of Lorentz invariance) [2]:

$$\Phi_{\mu\nu}{}^{\rho\sigma ab}{}_{cd} = a_1 \delta_{\mu\nu}^{\rho\sigma} \delta_{cd}^{ab} + b_1 (e_\mu^f)(e_\nu^g) \epsilon_{fg}{}^{kl} (e_k^\rho)(e_l^\sigma) \delta_{cd}^{ab} + c_1 \delta_{\mu\nu}^{\rho\sigma} \epsilon_{cd}^{ab} + d_1 \epsilon_{\mu\nu}{}^{\rho\sigma} \epsilon_{cd}^{ab}, \quad (49)$$

where a_1, b_1, c_1, d_1 are parameters determined by the equations of motion. Using the notations of Ref. [2] for Eq. (49), we have:

$$\Phi = a_1 + b_1 * + c_1 \star + d_1 * \star. \quad (50)$$

In the present paper, in contrast to Refs. [1] and [2], we do not consider the first class of solutions for Φ , when we have $a_1 = c_1 = d_1 = 0$ and $b_1 = 1$. We investigate the second

class of solutions (see [2]) for ansatz (49) with any non-trivial values of parameters. In this case, according to Eq. (46), we have:

$$B = \Omega F, \quad (51)$$

where

$$\Omega = -\frac{1}{2} \left(\Phi + \frac{1}{3} \Phi \Phi \Phi \right)^{-1}. \quad (52)$$

Using the ansatz (49) (or (50)) for Φ , it is easy to obtain that Ω has the structure analogous to (49), (50):

$$\Omega = a_2 + b_2 * + c_2 \star + d_2 * \star, \quad (53)$$

with new parameters a_2, b_2, c_2, d_2 determined by the equations of motion. Taking into account the equations of motion and the result (51), we can present the following action for the Graviweak unification:

$$I(A, \Omega) = \frac{1}{2g_{uni}} \int_{\mathfrak{M}} \langle \Omega F F \rangle, \quad (54)$$

where

$$\langle \Omega F F \rangle = \frac{d^4 x}{32} \epsilon^{\mu\nu\rho\sigma} \Omega_{\mu\nu}{}^{\varphi\chi IJ}{}_{KL} F_{\varphi\chi IJ} F_{\rho\sigma}{}^{KL}. \quad (55)$$

5.2 Symmetry breaking to gravity

The ansatz (51)-(55) for Ω distinguishes a subalgebra $\tilde{\mathfrak{g}}$ of the algebra $\mathfrak{g} = \mathfrak{spin}(4, 4)$, and we can consider separate parts of our connection A :

$$A = \frac{1}{2} A^{IJ} \gamma_{IJ} = \frac{1}{2} (A^{ab} \gamma_a \gamma_b + A^{am} \gamma_a \gamma_m + A^{ma} \gamma_m \gamma_a + A^{mn} \gamma_m \gamma_n), \quad (56)$$

or

$$A = \frac{1}{2} \omega + \frac{1}{4} E + A_W, \quad (57)$$

where the gravitational spin connection is:

$$\omega = \frac{1}{2} \omega^{ab} \gamma_a \gamma_b, \quad (58)$$

the frame-Higgs connection

$$E = E^{am} \gamma_a \gamma_m \quad (59)$$

is valued in the off-diagonal complement of $\mathfrak{spin}(4, 4)$, and the weak gauge field is:

$$A_W = \frac{1}{2} A^{mn} \gamma_m \gamma_n. \quad (60)$$

In Eqs. (56)-(60) the indices $a, b \in \{0, 1, 2, 3\}$ are used to sum over a subset of $I, J \in 1, 2, \dots, 7, 8$ for $I, J = 1, 2, 3, 4$, and thereby select a $\mathfrak{spin}(1, 3)$ subalgebra of $\mathfrak{spin}(4, 4)$. The indices $m, n \in \{5, 6, 7, 8\}$ sum over the rest, and further we use $\tilde{m}, \tilde{n} = m - 5, n - 5$, i.e. $\tilde{m}, \tilde{n} \in \{0, 1, 2, 3\}$. Here $\gamma_a = \{\gamma_0, \vec{\gamma}\}$ and $\gamma_{\tilde{m}} = \{\mathbf{1}, \gamma_0 \vec{\gamma}\}$. We have chosen $\gamma_I = 1, \dots, 8 = \{1_4, \gamma_0, \gamma_i, \gamma_0 \gamma_i\}$, and $\tilde{m} = 0, 1, 2, 3$ correspond to $m = I = 5, 6, 7, 8$.

Since matrix A^{IJ} is antisymmetric, we have antisymmetric matrices ω^{ab} and $A_W^{\tilde{m}\tilde{n}}$, but (see [2]):

$$E^{a\tilde{m}} = e_\mu^a \phi^{\tilde{m}} dx^\mu, \quad (61)$$

where the fields $\phi^{\tilde{m}}$ are four components of the complex scalar Higgs field.

5.3 The Left and Right worlds of the Universe

Developing the ideas of Refs. [1, 3], we distinguish the Left and Right worlds of the Universe, considering the graviweak unified model in both sectors of the Universe, visible and invisible, which are described respectively by the following connections:

$$A^{IJ} = A_L^{IJ} = A^{(+)IJ}, \quad (62)$$

$$A'^{IJ} = A_R^{IJ} = A^{(-)IJ}. \quad (63)$$

In Ref. [3] we suggested to describe the gravity in the visible Universe by the self-dual left-handed Plebanski's gravitational action, while the gravity in the invisible Universe – by the anti-self-dual right-handed gravitational action. As it was shown in Section 3, the best way to study many aspects of the Lorentz group is via its Lie algebra. Since the Lorentz group is $SO(1,3)$, its Lie algebra is reducible and can be decomposed into two copies of the Lie algebra:

$$\mathfrak{so}(1, 3)_C = \mathfrak{sl}(2, C)_L \oplus \mathfrak{sl}(2, C)_R. \quad (64)$$

In particle physics, a state that is invariant under one of these copies of $SO(1, 3)_C$ is said to have chirality, either left-handed or right-handed, according to which copy of $SO(1, 3)_C$ it is invariant under. Self-dual tensors transform non-trivially only under $SL(2, C)_L$ and are invariant under $SL(2, C)_R$. By this reason, they are called "left-handed" tensors. Similarly, anti-self-dual tensors, non-trivially transforming only under $SL(2, C)_R$, are called right-handed tensors. These self-dual and anti-self-dual tensors $\omega^{(\pm)ab}$ have only three independent components given by $ab = 0i$ ($i = 1, 2, 3$):

$$\omega^{(\pm)i} = \pm 2\omega^{(\pm)0i}. \quad (65)$$

As a result, we have the Left world of the Universe, described by the left-handed self-dual 1-form connections:

$$A = A_L = A^{(+)} = \frac{1}{2}\omega + \frac{1}{4}E + A_W, \quad (66)$$

and the Right world of the Universe, described by the right-handed anti-self-dual 1-form connections:

$$A' = A_R = A^{(-)} = \frac{1}{2}\omega' + \frac{1}{4}E' + A'_{W'}, \quad (67)$$

where gauge fields $A^{(\prime)}$ are A in L-world and A' in R-world. For the weak gauge sector we have:

$$A_W^{(\prime)} = \frac{1}{2}A_W^{(\prime)\tilde{m}\tilde{n}}\gamma_{\tilde{m}}\gamma_{\tilde{n}}, \quad (68)$$

which are valued in $\mathfrak{su}(2)_{L,R}$ -algebra, respectively. Then gauge fields $A_W^{(\prime)\tilde{m}\tilde{n}}$ have only three non-zero components:

$$A_W^{(\prime)i} = \pm 2A_W^{(\prime)0i}, \quad (69)$$

and the vector fields $A_W^{(\prime)i}$ ($i = 1, 2, 3$) transform as adjoint vectors under the corresponding weak $SU(2)_{L,R}$ gauge group, respectively.

Taking into account the self- (or anti-self) duality, we see in the ansatz (53) the following equivalence:

$$a_2 = c_2 \star \quad \text{and} \quad b_2 \star = d_2 \star \star.$$

Then instead of (53), we have:

$$\Omega = a_2 + b_2 \star. \quad (70)$$

This ansatz leads only to the topological terms of gravity in the total action, which we temporarily won't consider. Then, in contrast to (49), we have considered the ansatz of the following type, which also is allowed:

$$\begin{aligned} \Omega_{\mu\nu}{}^{\varphi\chi}{}^{ab}{}_{cd} &= a \epsilon_{\mu\nu}{}^{\alpha\varphi}(e_\alpha^a)(e_\beta^b)(e_c^\chi)(e_d^\beta) + b \epsilon_{\mu\nu}{}^{\varphi\chi}(e_\alpha^a)(e_\beta^b)(e_c^\alpha)(e_d^\beta) \\ &\quad + c \epsilon_{\mu\nu}{}^{\alpha\beta}(e_\alpha^a)(e_\beta^b)(e_c^\varphi)(e_d^\chi), \end{aligned} \quad (71)$$

and

$$\Omega_{\mu\nu}{}^{\varphi\chi}{}^{a\tilde{m}}{}_{c\tilde{n}} = (a + b + c)\epsilon_{\mu\nu}{}^{\varphi\chi}\delta_{c\tilde{n}}^{a\tilde{m}}, \quad (72)$$

$$\Omega_{\mu\nu}{}^{\varphi\chi}{}^{\tilde{m}\tilde{n}}{}_{\tilde{k}\tilde{l}} = (a + b + c)\epsilon_{\mu\nu}{}^{\varphi\chi}\delta_{\tilde{k}\tilde{l}}^{\tilde{m}\tilde{n}}. \quad (73)$$

Now we are ready to consider the action which is a consequence of our graviweak unification.

5.4 The action of the graviweak unified model with the renormalizable gravity in the left and right worlds

Using all our notations and equations (57)-(61), we can write:

$$F_{\mu\nu}^{ab} = \frac{1}{2}(\omega_{\mu\nu}^{ab} - \frac{1}{8}\Sigma_{\mu\nu}^{ab}\phi^2), \quad (74)$$

where

$$\omega_{\mu\nu}^{ab} = \partial_\mu \omega_\nu^{ab} - \partial_\nu \omega_\mu^{ab} + \frac{1}{2}[\omega_\mu^{ac}, \omega_\nu^{cb}], \quad (75)$$

and

$$\Sigma_{\mu\nu}^{ab} = e^a \wedge e^b \quad (76)$$

with the "metricity constrain":

$$\Sigma^a \wedge \Sigma^b = \frac{1}{3} \delta^{ab} \Sigma_c \wedge \Sigma^c. \quad (77)$$

Then

$$F_{\mu\nu}^{a\tilde{m}} = \frac{1}{4} T_{\mu\nu}^a \phi^{\tilde{m}} - \frac{1}{8} (e_\mu^a \mathcal{D}_\nu^{\tilde{m}\tilde{n}} - e_\nu^a \mathcal{D}_\mu^{\tilde{m}\tilde{n}}) \phi^{\tilde{n}}, \quad (78)$$

where

$$T_{\mu\nu}^a = \partial_\mu e_\nu^a - \partial_\nu e_\mu^a + \frac{1}{2}[\omega_\mu^{ab}, e_\nu^b] \quad (79)$$

is a torsion, and

$$F_{\mu\nu}^{\tilde{m}\tilde{n}} = F_W^{\tilde{m}\tilde{n}} \quad (80)$$

is the curvature of the weak gauge field. The action (54) was calculated, using Eq. (55) with ansatz expressions (71)-(73). Also Eqs. (74)-(80) were used. The Eq. (55) allows us to return to the GR formalism, when the dynamics is described by the metric tensor $g_{\mu\nu}$. Ignoring the fermionic matter, we have no source for torsion, and the torsion (79) is absent in the action. Then the result is given by the following integral:

$$\begin{aligned} I_{(GW)} = & -\frac{1}{4g_{uni}} \int_{\mathfrak{M}} d^4x \sqrt{-g} \left[\frac{(a+b+c)}{8} \left(\frac{1}{2} R |\phi|^2 - \frac{3}{4} |\phi|^4 \right) + \frac{1}{16} (a R_{\mu\nu} R^{\mu\nu} + b R^2 + c R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}) \right. \\ & \left. + (a+b+c) \left(\frac{1}{2} \mathcal{D}_\mu \phi \mathcal{D}^\mu \phi + \frac{1}{4} F_W^i{}_{\mu\nu} F_W^{i\mu\nu} \right) \right]. \end{aligned} \quad (81)$$

Considering the Friedmann-Lemaitre-Robertson-Walker (FLRW) homogeneous and isotropic metric, we assume that the Gauss-Bonnet topological action term vanishes, i.e. $c = 0$, because the metric is conformally flat [68]. Here we want to emphasize, that the graviweak action of Ref. [1] corresponds to the case $a = b = 0$ and $c = 3/2$.

However, in the present paper the action is considered in terms of the following expression:

$$\begin{aligned} I_{(GW)} = & -\frac{1}{4g_{uni}} \int_{\mathfrak{M}} d^4x \sqrt{-g} \left[\frac{w}{8} \left(\frac{1}{2} R |\phi|^2 - \frac{3}{4} |\phi|^4 \right) \right. \\ & \left. + \frac{1}{16} (a R_{\mu\nu} R^{\mu\nu} + b R^2) + w \left(\frac{1}{2} \mathcal{D}_\mu \phi^\dagger \mathcal{D}^\mu \phi + \frac{1}{4} F_W^i{}_{\mu\nu} F_W^{i\mu\nu} \right) \right], \end{aligned} \quad (82)$$

where $w = a + b$.

The parameters w, a, b are coupling constants of the higher derivative gravity.

Assuming that at the first stage of the evolution (before inflation) the Universe had the de Sitter spacetime, which is a maximally symmetric Lorentzian manifold with a constant and positive background scalar curvature R_0 , we obtain a nontrivial vacuum solution to the action (82). This de Sitter spacetime has a non-vanishing Higgs vacuum expectation value (VEV):

$$\phi_0^2 \equiv \langle \phi_0^2 \rangle = v^2 = \frac{1}{3}R_0, \quad (83)$$

$v = \langle \phi_0 \rangle$ is the vacuum expectation value (VEV)). The small fluctuations near this vacuum expectation value are given by the fields η :

$$\phi^m = v + \eta^m. \quad (84)$$

As a result, we obtain the following action:

$$\begin{aligned} I_{(GW)} = & -\frac{1}{4g_{uni}} \int_{\mathfrak{M}} d^4x \sqrt{-g} \left[\frac{wv^2}{8} \left(\frac{R}{2} (1 + |\eta|^2/v^2) - \Lambda_0 (1 + |\eta|^2/v^2)^2 \right) \right. \\ & \left. + \frac{1}{16} (aR_{\mu\nu}R^{\mu\nu} + bR^2) + w \left(\frac{1}{2} \mathcal{D}_\mu \eta^\dagger \mathcal{D}^\mu \eta + \frac{1}{4} F_{W\mu\nu}^i F_W^{i\mu\nu} \right) \right], \end{aligned} \quad (85)$$

in which the parameters a, b, w are "bare" coupling constants corresponding to the Planck scale.

Here we can introduce the following relations:

1) the "bare" cosmological constant (the contribution of the gravitational zero modes) is:

$$\Lambda_0 = \frac{3}{4}v^2 = \frac{1}{4}R_0; \quad (86)$$

2) the squared coupling constant of the weak interactions $g_W \equiv g_2$ at the Planck scale is:

$$g_W^2 = \frac{4g_{uni}}{w}; \quad (87)$$

3) the Newton constant G_N and the reduced Planck mass are:

$$(M_{Pl}^{red.})^2 = (8\pi G_N)^{-1} = \frac{1}{\kappa^2} = \frac{wv^2}{32g_{uni}} = \frac{v^2}{8g_W^2}. \quad (88)$$

Considering the running constant $\alpha_2^{-1}(\mu)$, where $\alpha_2 = g_2^2/4\pi$, it is possible to make an extrapolation of this value to the Planck scale [66,67], which gives the following result:

$$\alpha_2(M_{Pl}) \sim 1/50, \quad g_{uni} \sim 0.1. \quad (89)$$

Having substituted in Eq. (88) the values of g_W and $G_N = 1/8\pi(M_{Pl}^{red.})^2$, where $M_{Pl}^{red.} \approx 2.43 \cdot 10^{18}$ GeV, it is easy to obtain the VEV's value v , which in this case is located near the Planck scale:

$$v = v_2 \approx 3.5 \cdot 10^{18} \text{ GeV}. \quad (90)$$

Then we have the following OW action near the Planck scale:

$$I_{(OW)} = \int_{\mathfrak{M}} d^4x \sqrt{-g} [L_{(GW)} + L_{U(4)}], \quad (91)$$

where the graviweak unification is described by the part of the total action $I_{(OW)}$:

$$\begin{aligned} I_{(GW)} = & - \int_{\mathfrak{M}} d^4x \sqrt{-g} L_{(GW)} \simeq - \int_{\mathfrak{M}} d^4x \sqrt{-g} \left[\frac{3(M_{Pl}^{red.})^2}{4\Lambda_0} \left(\frac{R}{2} |\phi|^2 - \frac{3}{4} |\phi|^4 \right) \right. \\ & \left. + \frac{1}{64g_{uni}} (a R_{\mu\nu} R^{\mu\nu} + b R^2) + \frac{1}{g_W^2} \left(\frac{1}{2} \mathcal{D}_\mu \phi^\dagger \mathcal{D}^\mu \phi + \frac{1}{4} F_{W\mu\nu}^i F^{i\mu\nu}_W \right) \right]. \end{aligned} \quad (92)$$

Spontaneous symmetry breaking of the $Spin(4, 4)$ -invariant action of the graviweak unification by non-trivial vacuum expectation values gives the following actions in the ordinary and mirror worlds:

$$\begin{aligned} I_{(GW)}^{(\prime)} = & - \frac{1}{4g_{uni}} \int_{\mathfrak{M}} d^4x \sqrt{-g^{(\prime)}} \left[\frac{w^{(\prime)}}{8} \left(\frac{1}{2} R^{(\prime)} |\phi^{(\prime)}|^2 - \frac{3}{4} |\phi^{(\prime)}|^4 \right) + \frac{1}{16} (a^{(\prime)} R_{\mu\nu}^{(\prime)} R^{(\prime)\mu\nu} + b^{(\prime)} R^{(\prime)2} \right. \\ & \left. + w^{(\prime)} \left(\frac{1}{2} \mathcal{D}_\mu \phi^{(\prime)\dagger} \mathcal{D}^\mu \phi^{(\prime)} + \frac{1}{4} F_{W^{(\prime)}\mu\nu}^{(\prime)i} F^{(\prime)i\mu\nu}_{W^{(\prime)}} \right) \right], \end{aligned} \quad (93)$$

with $w^{(\prime)} = a^{(\prime)} + b^{(\prime)}$. Here we assume the equality of the graviweak unification parameters: $g'_{uni} = g_{uni}$, which is a consequence of the assumption that TOE existed at the early stage of the Universe, when MP was unbroken.

6 Super-renormalizable gravity and the problem of unitarity

The development of a quantum field theory of the Einstein-Hilbert GR faced a serious problem: quantum gravity based on the GR is non-renormalizable, the traditional methods of renormalization cannot be used to eliminate the ultraviolet divergences appearing in its perturbation theory.

Perturbative quantum gravity is a quantum theory of a spin two particle on a fixed background. Starting from the Einstein-Hilbert action (29), we introduce a splitting of the metric in a background part plus a fluctuation:

$$g_{\mu\nu} = g_{\mu\nu}^0 + \kappa h_{\mu\nu}, \quad (94)$$

where $h_{\mu\nu}$ is a graviton. Then we expand the action in powers of the fluctuation $\kappa h_{\mu\nu}$ around the fixed background $g_{\mu\nu}^0$ (it may be Minkowski metric $\eta_{\mu\nu}$).

In the four-dimensional gravitational theory the superficial degree of divergence $D = 2 + 2L$ increases with the number L of loops and thus we are forced to introduce an infinite number of counter terms, i.e. an infinite number of coupling constants. This circumstance makes the theory unpredictable.

An alternative way to quantize gravity is the introducing of some higher derivative terms into the classical action, treating them along with other lower-derivative (Einstein-Hilbert and cosmological) terms. Such a theory of gravity was developed in Refs. [68–86]. For example, adding generic fourth order derivative terms, one modifies propagator and vertices in such a way that the new quantum theory is renormalizable [69, 73]. This nice property leads to establish the asymptotic freedom in the UV limit [71, 73]. Including new terms with derivatives higher than four we obtain super-renormalizable theories of quantum gravity [79–85].

A first revolution in quantum gravity was introduced by Stelle [69], who suggested the following action of the higher derivative gravitational theory:

$$S = - \int d^4x \sqrt{-g} [\alpha R_{\mu\nu} R^{\mu\nu} + \beta R^2 + \frac{1}{2\kappa^2} R]. \quad (95)$$

This theory is renormalizable, but unfortunately contains a physical ghost (state of negative norm) breaking unitarity in the theory.

A problem of ghosts is a very serious and paramount task in the theory of quantum gravity. Recently a new gravitational theory was suggested, which is an approach to the quantum gravity. We can resume as follows the theoretical and observational consistency requirements for a full theory of quantum gravity: (i) classical solutions must be singularity-free; (ii) Einstein-Hilbert action should be a good approximation of the theory at a much smaller energy scale than the Planck mass; (iii) the spacetime dimension has to decrease with the energy in order to have a complete quantum gravitational theory in the ultraviolet regime; (iv) the theory has to be perturbatively renormalizable at the quantum level; (v) the theory has to be unitary, with no other pole in the propagator in addition to the graviton; (vi) spacetime is a single continuum of space and time, and in particular, the Lorentz invariance is not broken, consistently with observations.

In Refs. [68, 79–84] the Stelle theory was generalized to restore unitarity. They considered a modification of the Feynman rules where the coupling constants g_i are no longer constant, but function of the momentum p . For particular choices of $g_i(p)$ and $G_N(p)$ (gauge coupling constants and gravitational constant as functions of the 4-momenta), the propagators do not show any other pole above the standard particle content of the theory, therefore the theory is unitary. On the other hand the theory is also finite if the coupling constants go sufficiently fast to zero in the ultra-violet limit.

Super-renormalizable gravity (SRG) suggested in Refs. [68, 79–84] is well defined perturbatively at the quantum level. The corresponding gravitational Lagrangian is a

non-polynomial extension of the renormalizable quadratic Stelle theory [69] and it has the following general structure:

$$L = \frac{\alpha_k}{2\kappa^2} R + \alpha R_{\mu\nu} R^{\mu\nu} + \beta R^2 + R_{\mu\nu} h_2(-\square_\Lambda) R^{\mu\nu} + R h_0(-\square_\Lambda) R, \quad (96)$$

where \square is the covariant D'Alembertian operator, $\square_\Lambda := \square/\Lambda$, and Λ is an invariant mass scale; the two functions $h_i(-\square_\Lambda)$ ($i=0,2$) are not polynomial but entire, i.e. without poles or essential singularities; α_k, α, β are coupling constants subjected to quantum renormalizations.

Thus, there was introduced a nonlocal extension of the higher-derivative gravity, which is perturbatively renormalizable and unitary in any dimension D . The four-dimensional theory is easily obtained from the Stelle theory [69] by introducing in the action two entire functions, i.e. form factors, between the Ricci scalar square and the Ricci tensor square :

$$\begin{aligned} R^2 &\rightarrow R h_0(\square_\Lambda) R, \\ R_{\mu\nu} R^{\mu\nu} &\rightarrow R_{\mu\nu} h_2(\square_\Lambda) R^{\mu\nu}. \end{aligned} \quad (97)$$

The main reason for introducing the entire functions $h_i(z)$ ($i=0,2$) is to avoid ghosts and any other new pole in the graviton propagator.

The gravitational theory constructed in Refs. [68, 79–86] is renormalizable at one loop and finite from two loops on. Since only a finite number of graphs are divergent, then the theory is super-renormalizable.

Our graviweak unification theory suggests the action (92), in which a gravitational part of theory is super-renormalizable and asymptotically-free, but is not unitary in flat-space perturbation theory. With aim to make this theory unitary, it is necessary to introduce a nonlocal extension of the higher-derivative gravity, given by the procedure (97). Nevertheless, we can consider the transplanckian running of the "coupling constants" w, a, b given by the action (92) with aim to show the asymptotic freedom of this theory.

6.1 Running constants in the super-renormalizable gravity predicted by the graviweak unification

The study of the renormalization group flow of higher derivative gravity is based on the Schwinger-DeWitt technique, generalized by Barvinsky and Vilkovisky [87]. The one-loop renormalization constants in higher-derivative gravity were first calculated by Julve and Tonin [71]. The final correct result was obtained in Refs. [80, 85] (see also [86]). Using this result, we can calculate the gravitational functional renormalization group equations (FRGEs) for parameters w, a, b in the action (92) of the graviweak unification.

It is convenient to consider the running of coupling constants:

$$\gamma = \frac{w}{64g_{uni}}, \quad \tilde{a} = \frac{a}{64g_{uni}}, \quad \tilde{b} = \frac{b}{64g_{uni}}, \quad (98)$$

given by the RGEs:

$$\frac{d\gamma}{dt} = \beta_1, \quad \frac{d\tilde{a}}{dt} = \beta_2, \quad \frac{d\tilde{b}}{dt} = \beta_3, \quad (99)$$

when $t = \ln(\mu/\mu_0)$, and μ is a scale of energy. We choose the renormalization point $\mu_0 = M_{Pl}^{red.}$.

In the one-loop approximation we obtain the following results [80, 85, 86]:

$$\gamma(t) = \gamma(\mu_0) + \beta_1 t, \quad \tilde{a}(t) = \tilde{a}(\mu_0) + \beta_2 t, \quad \tilde{b}(t) = \tilde{b}(\mu_0) + \beta_3 t, \quad (100)$$

where

$$\beta_3 \approx \beta_2 = \frac{133}{10}, \quad \tilde{b}(M_{Pl}^{red.}) = -\tilde{a}(M_{Pl}^{red.}) = \frac{1}{12} \left(\frac{M_{Pl}^{red.}}{m} \right)^2, \quad (101)$$

according to the action (92).

For the dimensionless coupling constant $16\pi G_N \Lambda = \gamma^{-1}$ we obtain (see Ref. [86]):

$$\gamma(t) = \gamma(M_{Pl}^{red.}) + \frac{1 + 4\omega_1}{6} \beta_2 t, \quad (102)$$

where $\gamma(M_{Pl}^{red.}) \approx 0.32$ is given by the relations (98) and (86)-(90) ; $\omega_1 \approx -0.02$ is a fixed point [86] (in general, theory has two fixed points, see [86]). Finally, we obtain:

$$\lim_{t \rightarrow \infty} \gamma(t) \simeq 0.32 + 2.04t, \quad (103)$$

what means that the dimensionless gravitational coupling constant $G_N \Lambda (= 1/16\pi\gamma)$ is asymptotically free (here $\Lambda \equiv \Lambda_0$, which is a bare cosmological constant determined only by zero modes of gravitational fields).

The next development of this theory is given in the Part II of our investigation, where we consider algebraic spinors of the standard four-dimensional Clifford algebra with a left-right symmetry and imagine the embedding of the fermion families into the groups $U(4)_{L,R}$ with a final formation of the SM, SM'-groups of symmetry in the OW and MW, respectively. Then we consider the inflation model, predicted by our theory of the graviweak unification, and the Multiple Point Model (MPM), assuming the existence of several minima of the Higgs effective potential with the same energy density. We show that MPM is in agreement with our graviweak unification. The predictions of the top-quark and Higgs masses are given from the assumption that there exist two vacua into the SM: the first one – at the Electroweak scale ($v_1 \simeq 246$ GeV), and the second one – at the Planck scale ($v = v_2 \sim 10^{18}$ GeV).

7 Summary and Conclusions

1. In the present paper we constructed a theory of the unification of super-renormalizable gravity with weak $SU(2)$ gauge and Higgs fields.

2. We have given arguments that recent astrophysical and cosmological measurements lead to a model of the Mirror World with broken Mirror Parity (MP), in which the Higgs VEVs of the visible and invisible worlds are not equal: $\langle\phi\rangle = v$, $\langle\phi'\rangle = v'$ and $v \neq v'$. The parameter characterizing the violation of the MP is $\zeta = v'/v \gg 1$. We have used the estimate $\zeta \sim 100$, in accordance with Refs. [21–24]. In this model, we showed that the action for gravitational and $SU(2)$ Yang–Mills and Higgs fields, constructed in the ordinary world (OW), has a modified duplication for the hidden (mirror) sector of the Universe (MW).

3. We discussed the problems of communications between visible and invisible worlds. Mirror particles have not been seen so far in the visible world, and the communication between visible and hidden worlds is hard. This communication is given by the $L_{(mix)}$ -term of the total Lagrangian of the Universe.

4. We started with an extended $\mathfrak{g} = \mathfrak{spin}(4, 4)_L$ -invariant Plebanski action in the visible Universe, and with $\mathfrak{g} = \mathfrak{spin}(4, 4)_R$ -invariant Plebanski action in the MW.

5. We showed that the graviweak symmetry breaking leads to the following subalgebras: $\tilde{\mathfrak{g}} = \mathfrak{sl}(2, C)_L^{(grav)} \oplus \mathfrak{su}(2)_L$ – in the ordinary world, and $\tilde{\mathfrak{g}}' = \mathfrak{sl}(2, C)_R'^{(grav)} \oplus \mathfrak{su}(2)_R'$ – in the hidden world. These subalgebras contain the self-dual left-handed gravity in the OW, and the anti-self-dual right-handed gravity in the MW.

6. We developed a graviweak unification model in both, left-handed and right-handed (visible and invisible) sectors of the Universe. We considered the left and right worlds OW and MW, existing at the first stage of the Universe described by the symmetries $SL(2, C)_L^{(grav)} \times SU(2)_L \times U(4)_L$ and $SL(2, C)_R^{(grav)} \times SU(2)_R \times U(4)_R$, respectively.

7. In contrast to Refs. [1] and [2], we considered a general class of solutions for Ansatz, which gives any non-trivial values of parameters introducing the graviweak unification action. As a result, we propose a class of the super-renormalizable (finite) theory of gravity, providing an ultraviolet completion of the gravitational theory. This class of theory has a generalization, searching for the unitary, asymptotically-free and perturbatively consistent theory of quantum gravity. We have shown that the self-consistent graviweak unification is described by the higher-derivative super-renormalizable gravity, and this graviweak unification exists only at the high (Planck) scale.

8. The nontrivial vacuum solutions corresponding to the obtained actions are non-vanishing Higgs vacuum expectation values (VEVs): $v^{(\prime)} = \langle\phi^{(\prime)}\rangle = \phi_0^{(\prime)}$, which are not equal for the visible and mirror (or hidden) worlds.

9. Considering the graviweak unification, we obtained after a symmetry breaking Newton’s constant $8\pi G_N = 64g_{uni}/3v^2$, and the bare cosmological constant $\Lambda_0 = \frac{3}{4}v^2 = R_0/4$, where v is given by the second vacuum of the effective Higgs potential, and R_0 is a constant de Sitter spacetime background curvature.

10. We have calculated the graviweak action near the second local minimum of the effective Higgs potential, corresponding to the second vacuum with the VEV $v = v_2 \sim 10^{18}$ GeV.

11. We considered the renormalization group flow of the higher derivative gravity.

We presented (in the 1-loop approximation) the running of the super-renormalizable gravitational coupling constants, predicted by our graviweak unification model. We showed that the dimensionless gravitational coupling constant $G_N\Lambda_0$ is asymptotically free (here Λ_0 is a bare cosmological constant determined only by zero modes of gravitational fields).

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